WACCM: The High-Top Configuration of CESM

CESM Tutorial

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ACOM/NCAR

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Earth's atmosphere in the vertical

Model lid

WACCM-X

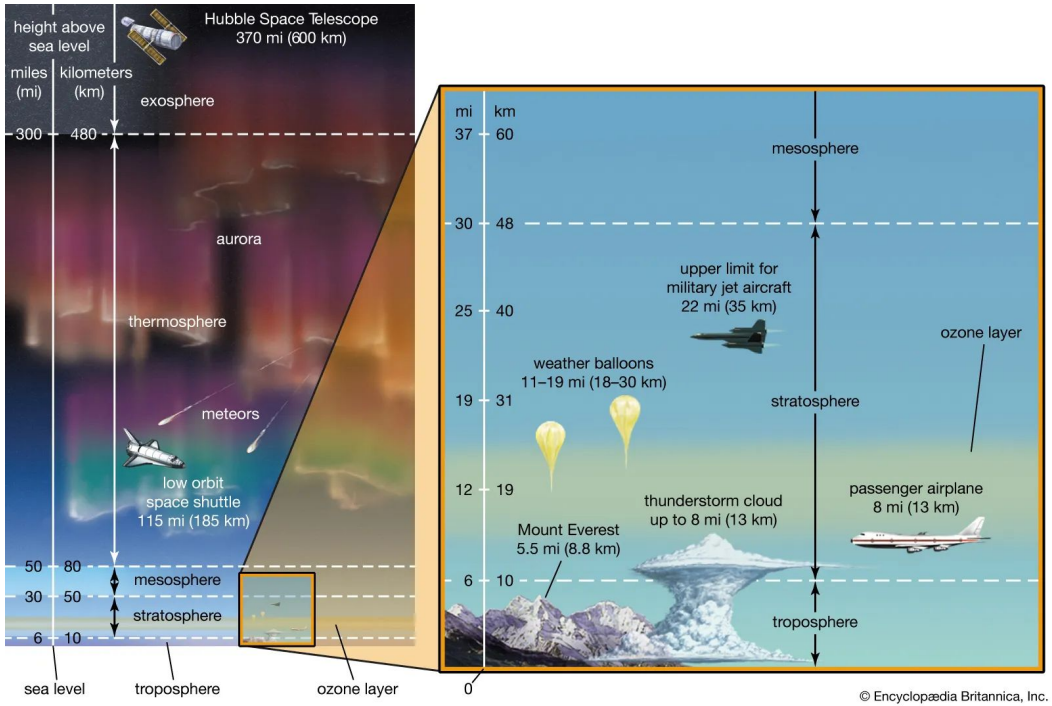
600 km

WACCM

140 km

CAM

45 km

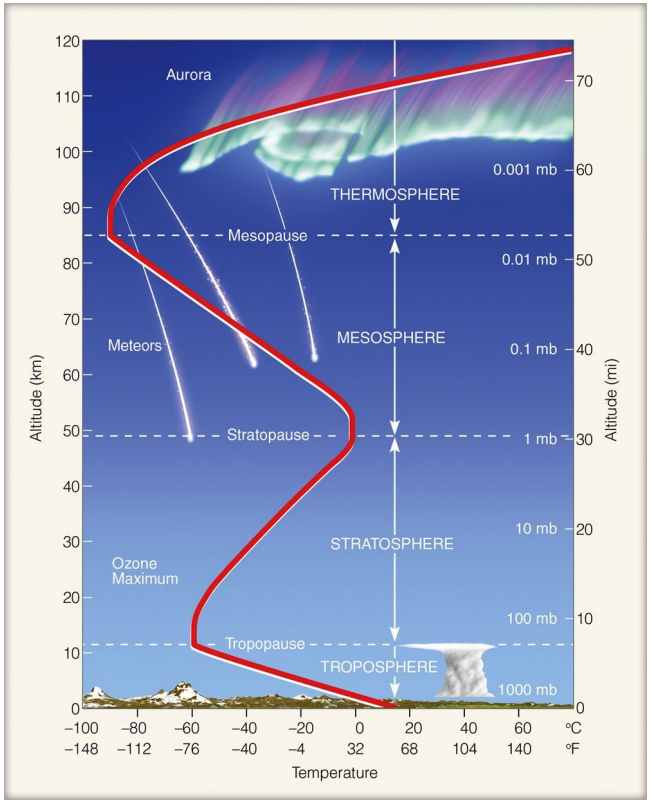


https://cdn.britannica.com/42/90442-050-6CB42E65/layers-atmosphere-Earth-phenomena-heights.jpg

- CAM, WACCM, and WACCM-X provide progressively higher model lids
- Higher lids require new and more comprehensive physics
- Focus of this overview is on WACCM
  - What physics do we need to resolve the atmosphere up to 140 km?
  - Why does this part of the atmosphere matter?
  - Why run this model?
  - How does this model perform?

Earth's atmosphere in the vertical

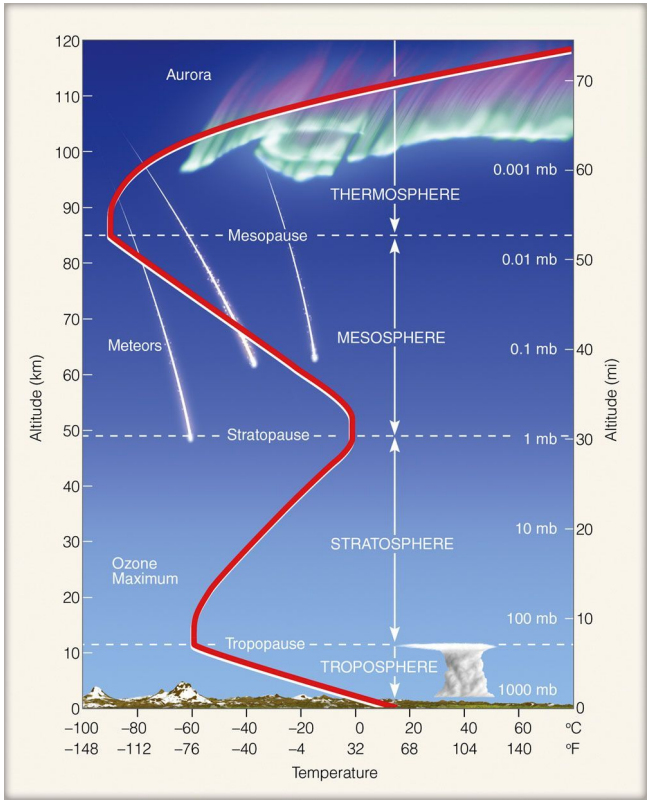
- Pressure decreases exponentially with altitude
- Temperature has a characteristic lapse rate in each sphere
  - Troposphere: set by convection
  - Stratosphere: iset by absorption of sunlight, ozone photochemistry, etc.
  - Mesosphere: set by weakening absorption of sunlight and enhanced infrared cooling with altitude
  - Thermosphere: set by absorption of high-energy sunlight



https://data.piercecollege.edu/weather/a.asp

Earth's atmosphere in the vertical

- Turbopause: where eddy and molecular diffusion are equal in strength
  - Roughly coincides with mesopause
  - Below turbopause, atmosphere is well-mixed
  - Above turbopause, lighter species become progressively more dominant with altitude
- Ozone
  - And the ozone hole - more later
- Airglow
- Auroras
- Meteors
- Aerosols from volcanoes, wildfires



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Motivation for WACCM

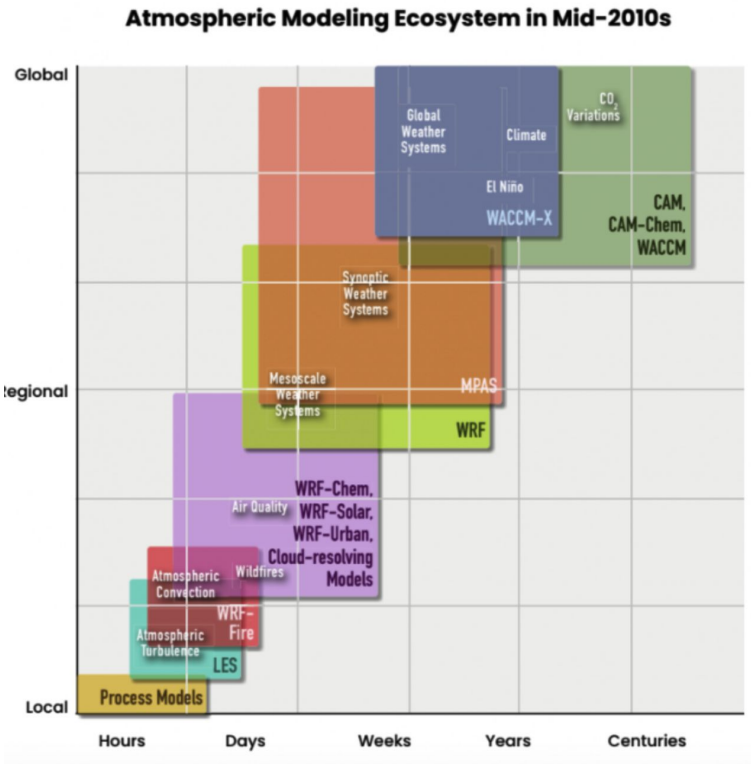
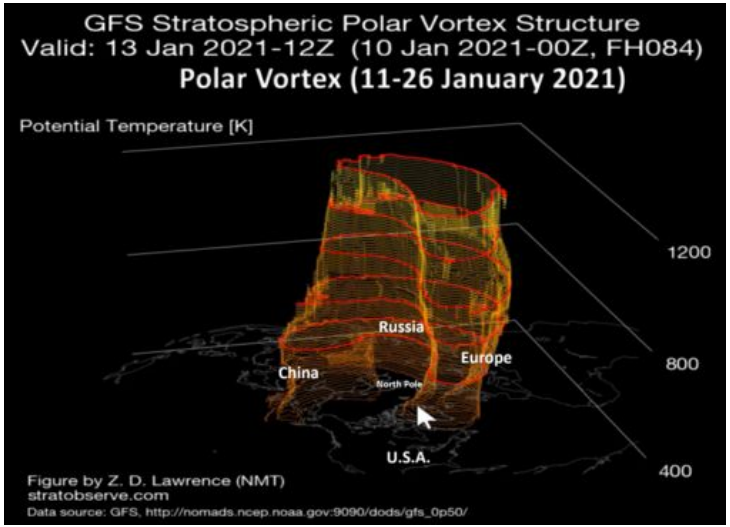


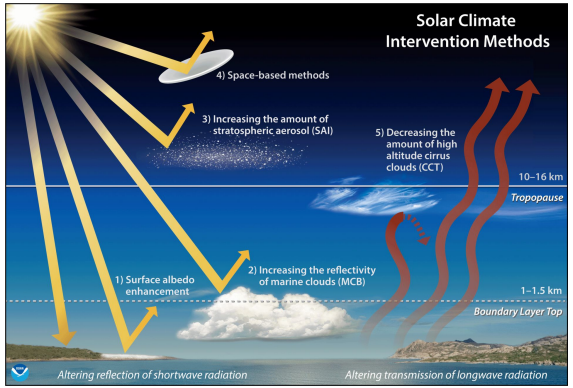
Image borrowed from a presentation by Mary Barth

Whole Atmosphere Community Climate Model (WACCM)

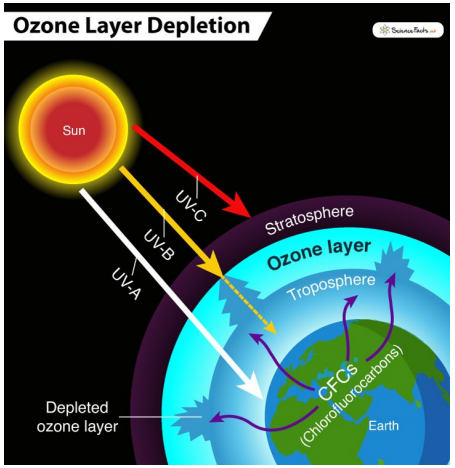
- The middle atmosphere (stratosphere and mesosphere) couples the surface and lower atmosphere to the upper atmosphere and space
  - Microscale to planetary scale, microseconds to centuries
  - Chemistry, aerosols, circulation, radiation
- We need a model that can simulate this coupling on short (weather/subseasonal-to-seasonal) and long (climate/paleoclimate) timescales

Motivation for WACCM





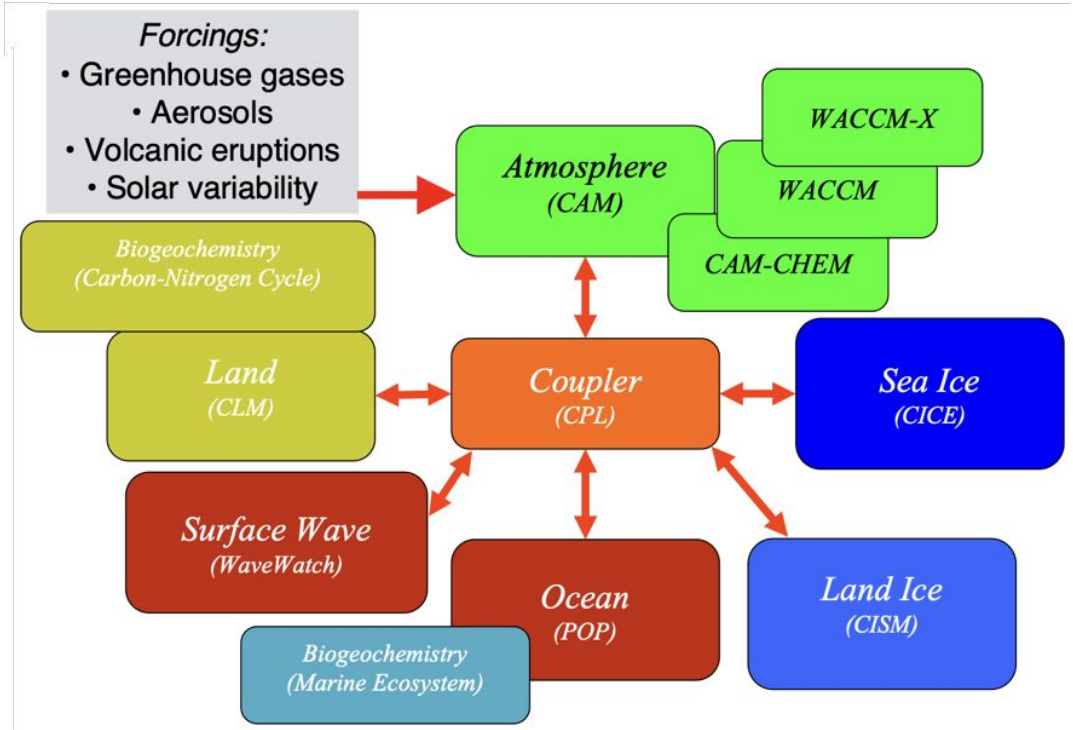
https://research.noaa.gov/2021/05/14/study-of-wildfire-plumes-provide-insights-into-methods-that-might-cool-the-planet/



https://www.sciencefacts.net/wp-content/uploads/2021/04/Ozone-Layer-Depletion.jpg

- Sudden stratospheric warmings: forecasting “windows of opportunity”, often with sustained surface weather impacts, including cold air outbreaks
- Climate geoengineering: especially using stratospheric aerosol injection
- Ozone depletion: due to human emissions of CFCs

How WACCM fits into CESM



- WACCM forms the atmosphere of component of CESM just like CAM

WACCM versus CAM

WACCM inherits the dycore and physics of CAM, and adds:

- Extension from surface to 6×10^{-6} hPa (~140 km), with 70 or 110 vertical levels
- Detailed neutral chemistry models
  - "middle atmosphere" (MA): catalytic cycles affecting ozone, heterogeneous chemistry on PSCs and sulfate aerosols, heating due to chemical reactions
  - "troposphere, stratosphere, mesosphere, and lower thermosphere" (TSMLT): adds chemistry affecting tropospheric air quality, organic chemistry
- Prognostic stratospheric aerosols derived from sulfur emissions
- Model of ion chemistry in the mesosphere/lower thermosphere (MLT), ion drag, auroral processes, and solar proton events
- EUV and non-LTE longwave radiation parameterizations
- Gravity wave drag deposition from vertically propagating GWs generated by orography, fronts, and convection
- Interactive QBO (quasi-biennial oscillation) derived from gravity and resolved wave forcing
- Molecular diffusion and constituent separation
- Thermosphere extension (WACCM-X) to ~500-700 km

WACCM versus WACCM-X

	WACCM6	WACCM-X v2
Vertical Levels	70, 88(SD), 110	126, 145(SD)
Model Top	$6x10^{-6}$ hPa (~140 km)	$4x10^{-10}$ hPa (500-700 km)
Horizontal Resolution	0.95˚x1.25˚, 1.9˚x2.5˚	1.9˚x2.5˚
Time step	30 minutes	5 minutes
Specified Dynamics	SD-WACCM6 option, or nudging_nml	SD-WACCM-X option, or nudging_nml
Chemistry	TSMLT (233), MA (99), SC (37)	MA (76)
QBO	0.95˚x1.25˚ or 1.9˚x2.5˚	Nudged
Tropospheric Physics	CAM6	CAM4
Radiation	RRTMG	CAM-RT
Tropospheric Aerosol	Interactive MAM4	Prescribed Bulk
Stratospheric Aerosol	Interactive MAM4	Prescribed
Non-orographic GW	Yes	Yes
Molecular Diffusion	minor	minor and major
Auroral Physics	Yes	Yes
Ions	E-region or E&D-region	E-region
Ion transport	No	Yes
E Dynamo	No	Yes

Gravity wave physics

- Three primary gravity wave schemes
  - Orographic: primarily affecting the stratospheric polar vortex
  - Frontal: primarily affecting the polar vortex and mesopause region
  - Convective: driving the QBO, impacting the mesopause region
- Schemes apply theoretical frameworks to trigger gravity wave generation and determine forcing

1. Orographic GWs:

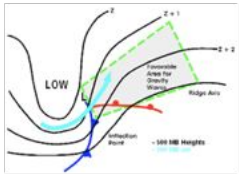
Uncertain: Efficiency

Orographic GWs:

- McFarlane (1987)
- 1 wave with c = 0
- Amplitude dependent on orography height and wean wind

2. Frontally generated GWs:

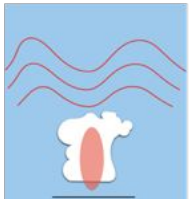
Uncertain: Efficiency, amplitude, phase speeds



- 40 waves with -100 < c < 100 m/s
- Gaussian distribution in phase speed centered at U 600 mb
- Constant wave amplitude

3. Convectively generated GWs:

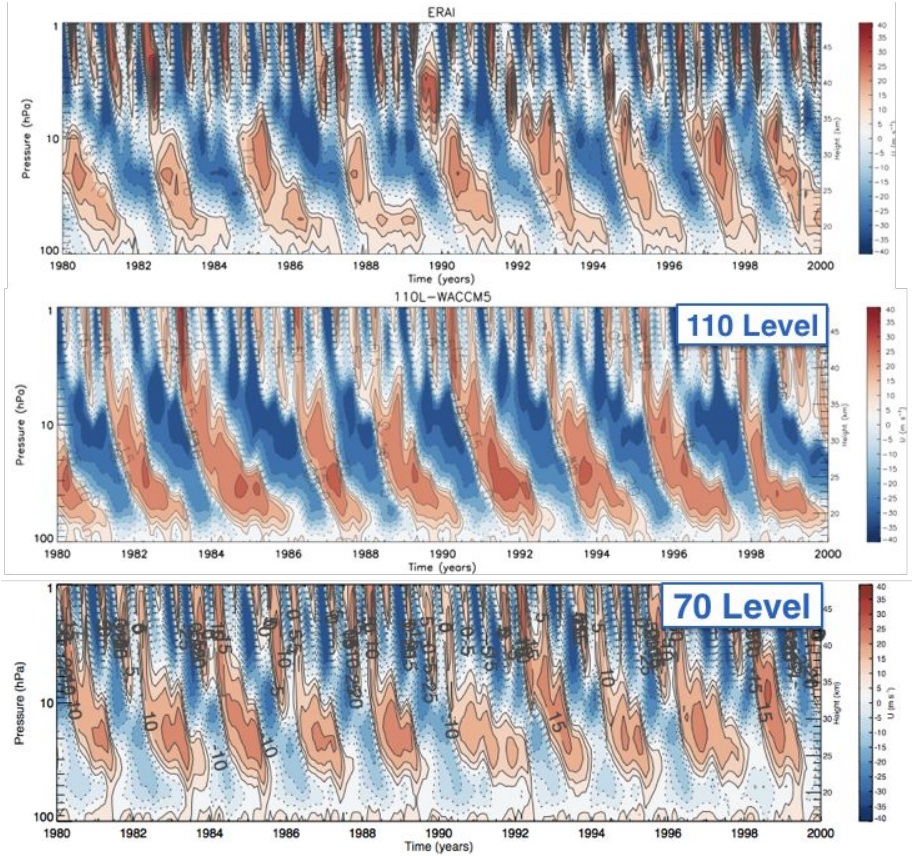
Uncertain: Efficiency, amplitude conversion



- 40 waves with -100 < c < 100 m/s
- Dominant c related to h (depth of heating)
- Wave Amplitude ∝ Q^2
- Wave spectrum impacted by wind in heating

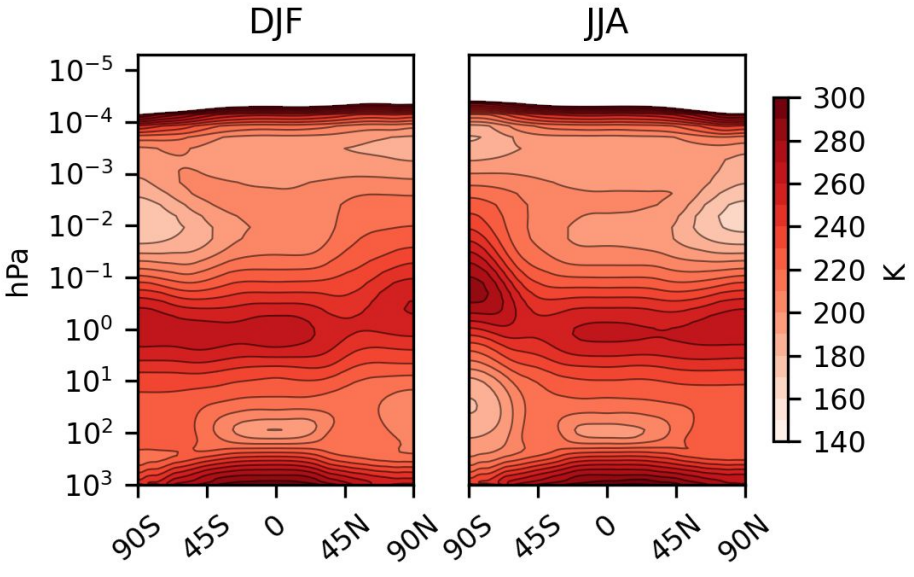
Beres et al. 2004 (Beres = Richter)

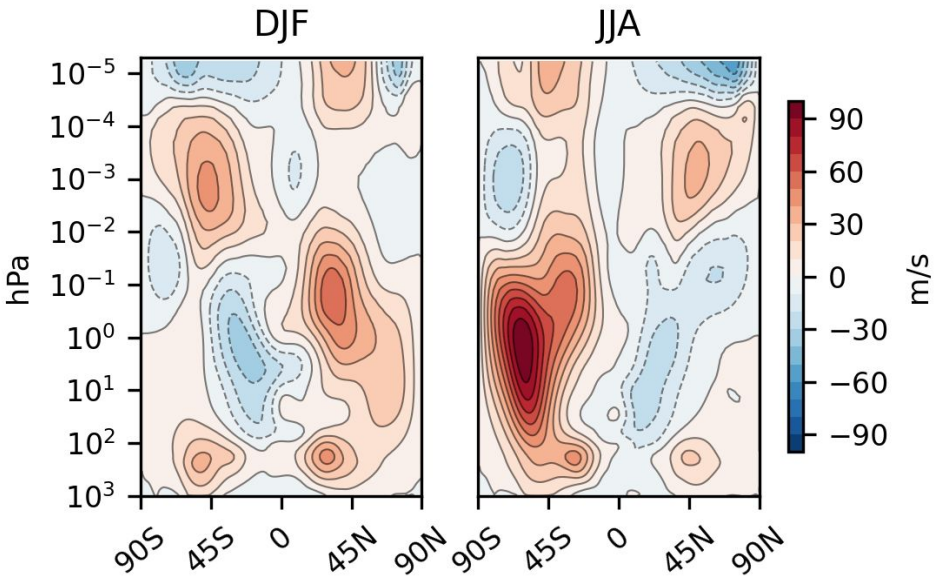
Gravity wave physics: the QBO



- QBO: natural result of a menagerie of upward-propagating waves with positive and negative phase speeds; momentum forcing “pulls” wind anomalies downward
  - Important modulator of teleconnections, stratospheric polar vortex variability
- High vertical resolution (~500 m in the 110L configuration) is needed to produce a reasonable internally-generated QBO

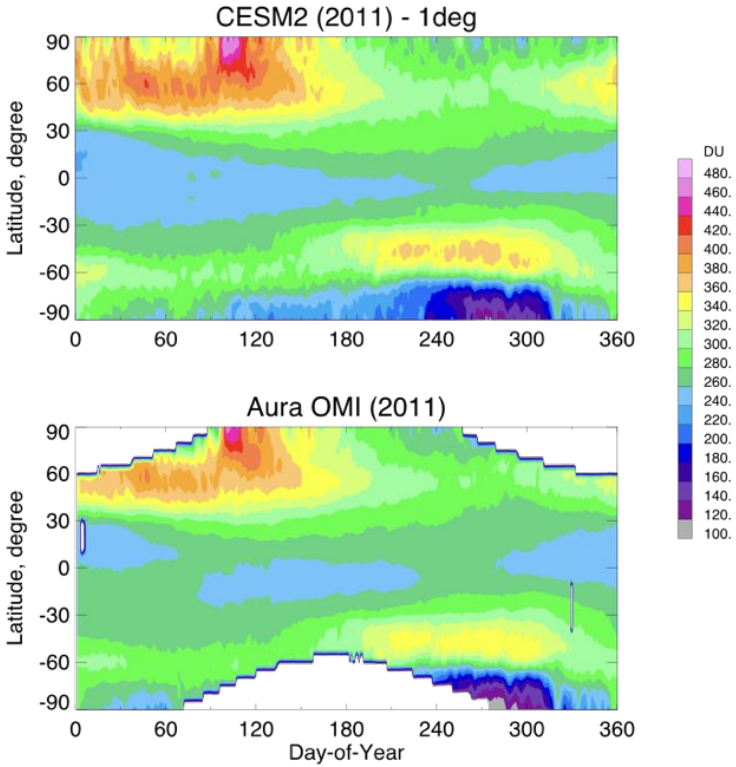
What does the atmosphere look like?





From 70L WACCM6 using the 1 deg. finite volume dynamical core

What does ozone look like?

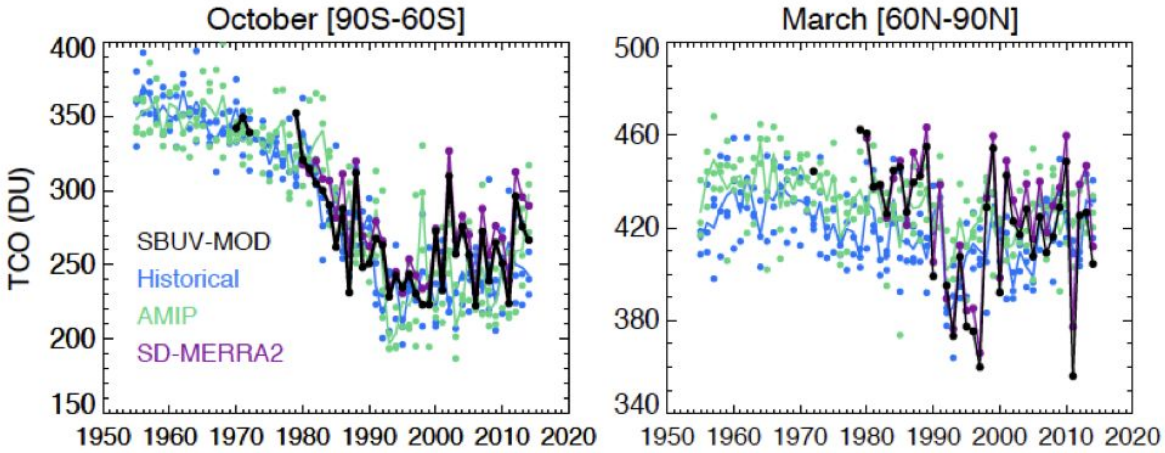


- WACCM6 has exceptional performance in reproducing total column ozone
  - Need to capture the chemistry and emissions, temperatures, and the circulation/transport

Courtesy of Doug Kinnison

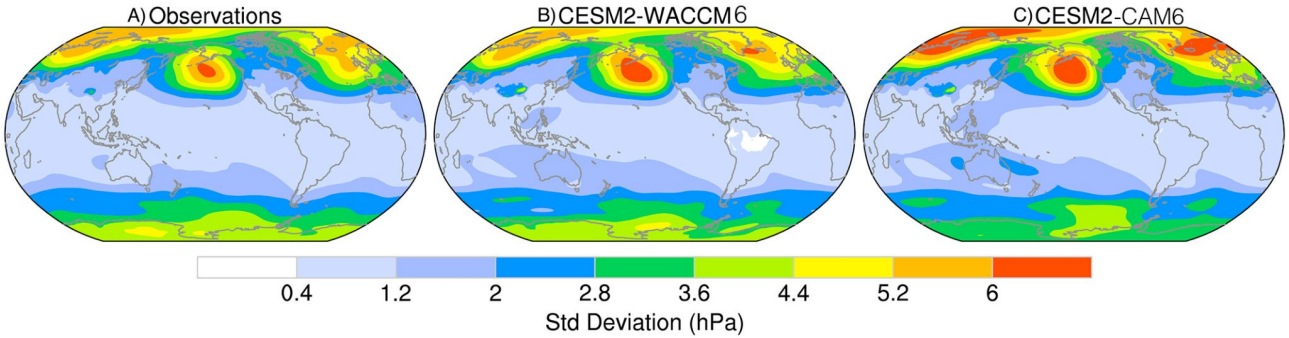
What about the ozone hole?

- WACCM6 captures the strength and timing of the Southern Hemisphere ozone hole
- When nudged to MERRA2 temperatures and winds (to ensure an apples-to-apples comparison of the chemistry with observations), the variability is well reproduced



From Gettelman et al. (2019)

Does the middle atmosphere matter for the surface?



From Gettelman et al. (2019)

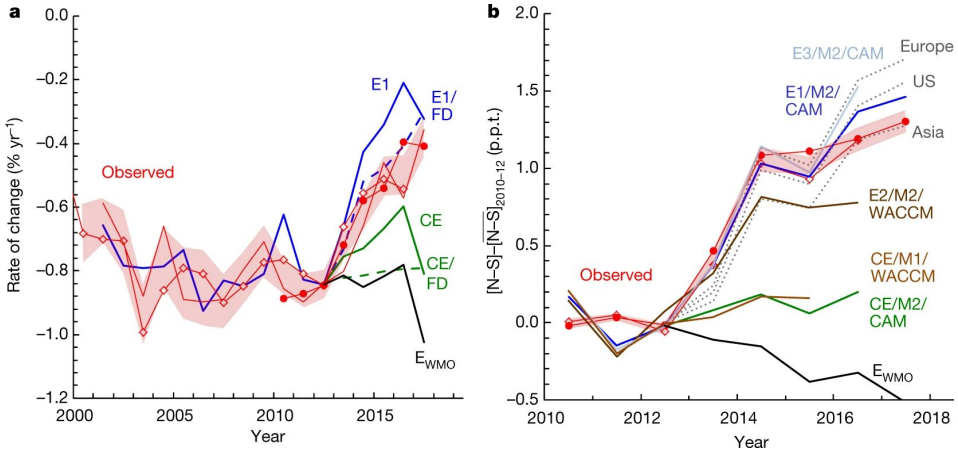
- WACCM6 better resolves the interannual standard deviation in sea level pressure in DJF than in CAM6
  - CAM6 is *too* variable!
- Stratosphere-troposphere coupling can link stratospheric circulation anomalies (with long lifetimes) to surface weather regimes

Applications: ozone depletion and emissions monitoring

An unexpected and persistent increase in global emissions of ozone-depleting CFC-11

Stephen A. Montzka ✉, Geoff S. Dutton, Pengfei Yu, Eric Ray, Robert W. Portmann, John S. Daniel, Lambert Kuijpers, Brad D. Hall, Debra Mondeel, Carolina Siso, J. David Nance, Matt Rigby, Alistair J. Manning, Lei Hu, Fred Moore, Ben R. Miller & James W. Elkins

Nature **557**, 413–417 (2018) | Cite this article



- In 2013, the steady reduction in CFC concentrations began slowing, implying an illegal production and release of CFC's banned by the Montreal Protocol
- NOAA scientists used WACCM experiments to show that the observed changes could not be explained by variability and the steady release of emissions from "banks" (like old refrigerators)
- Chinese government cracked down on rogue factories, and emissions have since declined (https://www.nytimes.com/2023/01/09/climate/ozone-hole-restoration-montreal-protocol.html)

Applications: polar vortex impacts

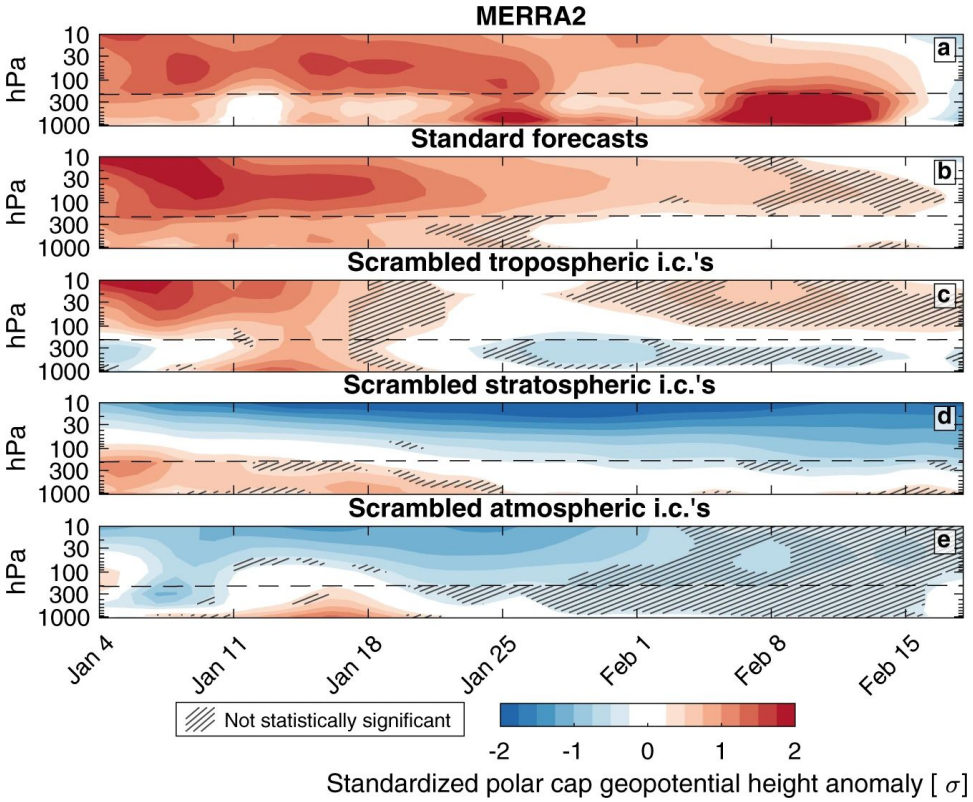
Article | Open Access | Published: 03 March 2022

Limited surface impacts of the January 2021 sudden stratospheric warming

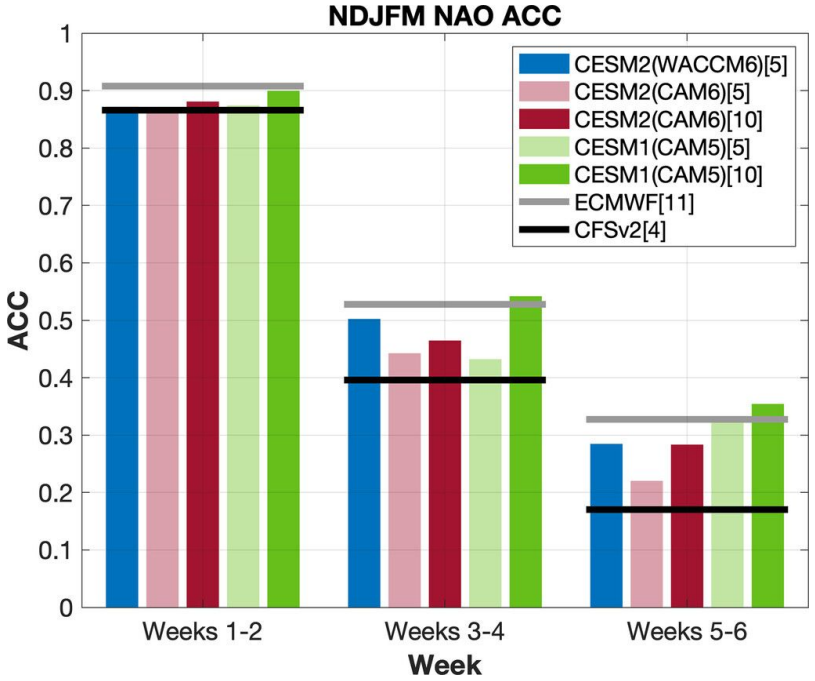
N. A. Davis, J. H. Richter, A. A. Glanville, J. Edwards & E. LaJoie

Nature Communications **13**, Article number: 1136 (2022) | Cite this article

- Sudden stratospheric warmings are often viewed as “downward” coupling events, where a weak vortex leads to a persistently-negative Northern Annular Mode at the surface
- WACCM6 forecasts reveal that the process is more like a two-way feedback process between the troposphere and stratosphere



Applications: subseasonal-to-seasonal prediction



Subseasonal Earth System Prediction with CESM2

Jadwiga H. Richter,[a] Anne A. Glanville,[a] James Edwards,[a] Brian Kauffman,[a] Nicholas A. Davis,[b] Abigail Jaye,[c] Hyemi Kim,[d] Nicholas M. Pedatella,[e] Lantao Sun,[f] Judith Berner,[c,a] Who M. Kim,[a] Stephen G. Yeager,[a] Gokhan Danabasoglu,[a] Julie M. Caron,[a] and Keith W. Oleson[a]

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[b] *Atmospheric Chemistry Observations and Modeling Laboratory, National Center for Atmospheric Research, Boulder, Colorado*
[c] *Mesoscale and Microscale Meteorology Laboratory, National Center for Atmospheric Research, Boulder, Colorado*
[d] *School of Marine and Atmospheric Sciences, Stony Brook University, State University of New York, Stony Brook, New York*
[e] *High Altitude Observatory, National Center for Atmospheric Research, Boulder, Colorado*
[f] *Colorado State University, Fort Collins, Colorado*

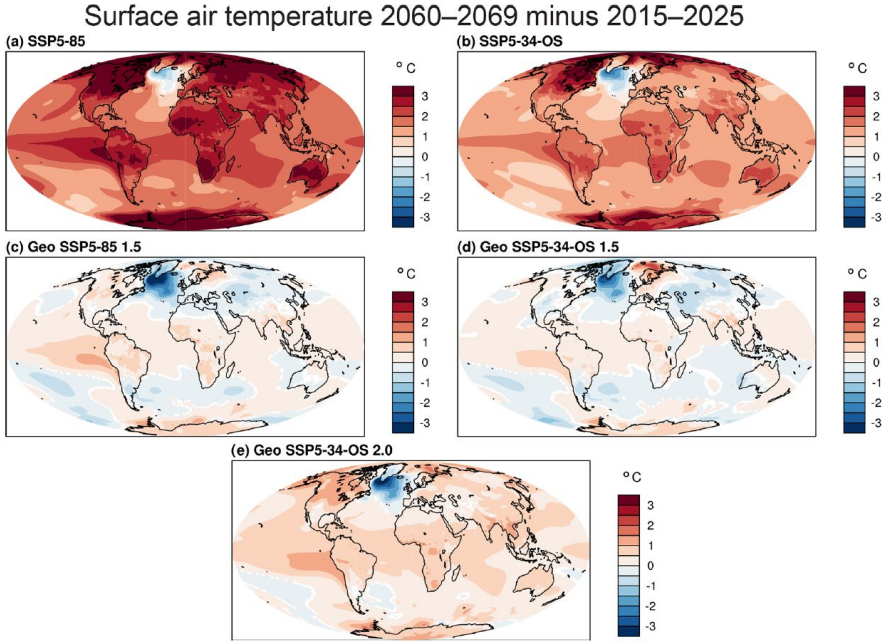
- NCAR currently maintains a realtime S2S ensemble that adheres to the SubX protocol
- An analysis of 1999-2019 hindcasts shows that WACCM6 shows greater skill than CAM6 in predicting the Northern Annular Mode at 3+ week lead times
- Potentially related to better resolution of stratosphere-troposphere coupling

Applications: geoengineering

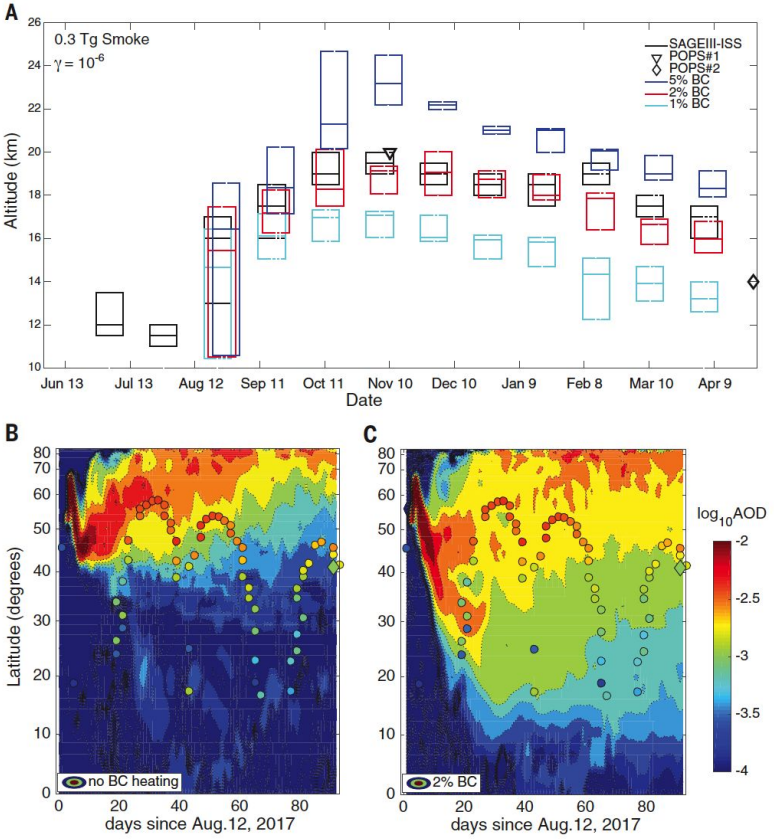
Reaching 1.5 and 2.0 °C global surface temperature targets using stratospheric aerosol geoengineering

Simone Tilmes[1], Douglas G. MacMartin[2], Jan T. M. Lenaerts[3], Leo van Kampenhout[4], Laura Muntjewerf[5], Lili Xia[6], Cheryl S. Harrison[7], Kristen M. Krumhardt[8], Michael J. Mills[1], Ben Kravitz[9,10], and Alan Robock[6]

- Stratospheric aerosol injection (SAI) is one possible way to offset greenhouse-gas-induced warming
- WACCM6 is one of the few models equipped to effectively study SAI, which requires comprehensive chemistry and accurate stratospheric transport
- Modeling results suggest that while SAI can limit global mean surface temperature changes, there are regional sensitivities and potentially adverse effects that need to be studied further



Applications: wildfire smoke in the stratosphere



ATMOSPHERIC CHEMISTRY

Black carbon lofts wildfire smoke high into the stratosphere to form a persistent plume

Pengfei Yu[1,2,3*], Owen B. Toon[4,5], Charles G. Bardeen[6], Yunqian Zhu[5], Karen H. Rosenlof[2], Robert W. Portmann[2], Troy D. Thornberry[1,2], Ru-Shan Gao[2], Sean M. Davis[2], Eric T. Wolf[5,7], Joost de Gouw[1,8], David A. Peterson[9], Michael D. Fromm[10], Alan Robock[11]

- The Canadian wildfires of 2017 were so severe that the smoke persisted in the stratosphere for 8 months
- Researchers using WACCM6 with CARMA (Community Aerosol and Radiation Model for Atmospheres) determined that the black carbon in the smoke absorbed sunlight and allowed the smoke to rise
- Smoke can reduce stratospheric NO2 through heterogeneous reactions, such that increasing wildfires in a warming climate may delay ozone recovery [Solomon et al. 2022]

What do you want to do?

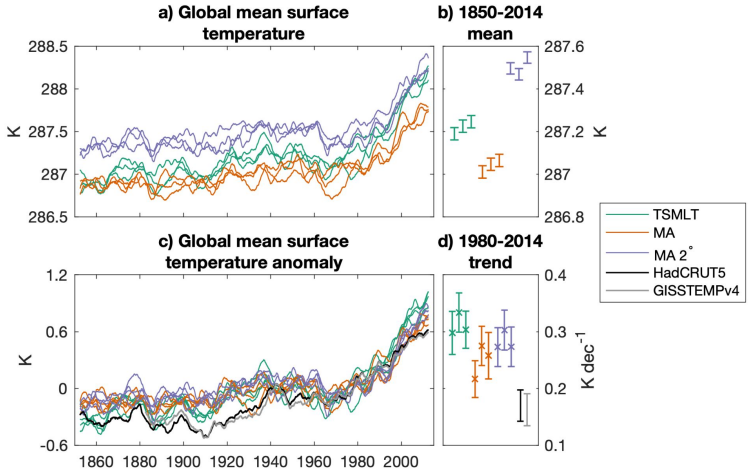
- WACCM6 is one of the most advanced configurations of CESM2, because it resolves
  - a greater vertical extent of the atmosphere
  - chemistry and aerosols
  - middle and upper atmosphere physics
  - vertical coupling by virtue of higher vertical resolution
- Many of our most pressing fundamental and applied scientific questions are at the intersection of multiple disciplines, with coupling across time and space
  - The WACCM enterprise at NCAR is a cross-lab endeavor between ACOM, CGD, and HAO, with broad external community involvement
- Could WACCM be the right model for you?

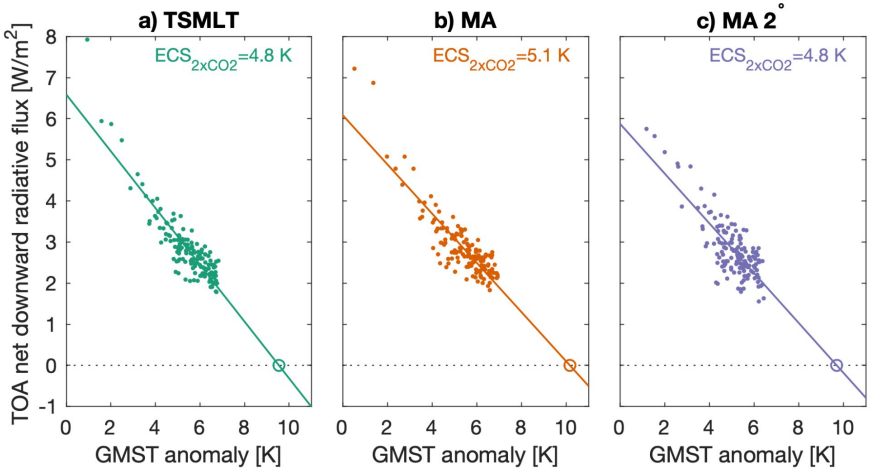
But how much does it cost?

Configuration	Resolution	Chemistry	Core-hours / simulation year
CAM6	1°, 32L	CAM	3,700
WACCM6	2°, 70L	MA	5,400
WACCM6	1°, 70L	TSMLT	22,000
WACCM6-SC	1°, 70L	SC	6,000

- Adding more vertical levels and interactive chemistry and aerosols is *not* cheap
- But we have more economical configurations at 2 deg. horizontal resolution that perform nearly as well for many purposes that cost a bit more than CAM (a formal evaluation paper is in review)

How do the more economical configurations perform?

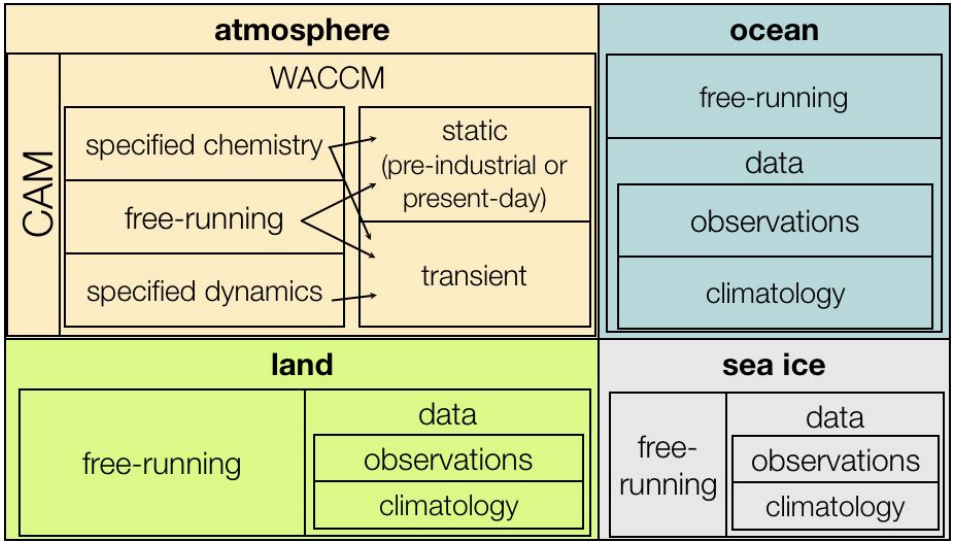




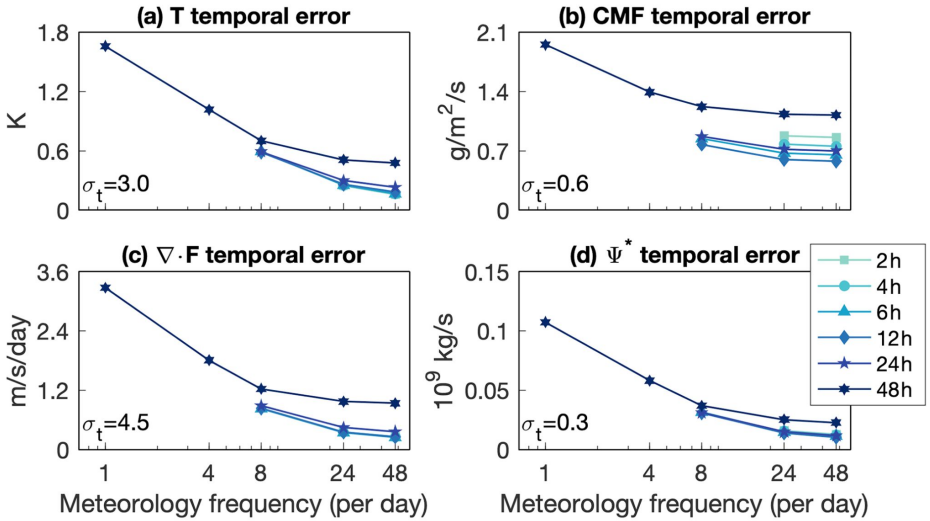
- There are some small differences in absolute global mean surface temperature among different configurations of WACCM6
  - Order 0.2 - 0.4 K
  - Due in part to differences in aerosol burdens
- Response to forcings is comparable - you can get a lot of mileage out of 2 deg. WACCM6 with MA chemistry

Possible configurations

- WACCM can be run with
  - interactive or specified chemistry
  - a free running atmosphere, or an atmosphere constrained to historical or specified meteorology via the specified dynamics scheme
    - Old approach: “SD” compsets
    - New approach: nudging namelist available in all atmospheric configurations and compsets
    - GEOS5, MERRA2 meteorology is available on GLADE



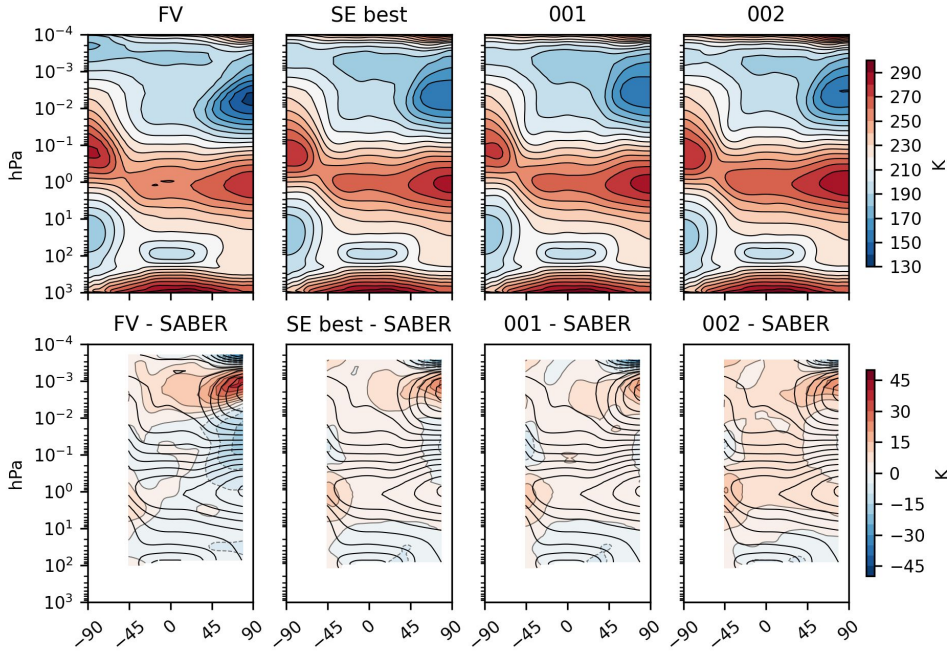
Specified dynamics to support good science



- Specified dynamics nudges all or a particular combination of the horizontal winds and temperature toward a reference meteorology
  - Typically a reanalysis, but could also be output from another CESM2 simulation
- This can be used to eliminate the uncertainty due to atmospheric variability
- Some best practices are described in Davis et al. (2022), "*Specified dynamics scheme impacts on wave-mean flow dynamics, convection, and tracer transport in CESM2 (WACCM6)*"

Future development

- WACCM7 is being developed for the spectral element dynamical core with 135 vertical levels
  - Will continue supporting nominal 1 and 2 deg. resolutions with both MA and TSMLT chemistry
- These new configurations will have reduced biases and improved simulation of the stratospheric polar vortex, the mesopause, and the QBO



Contacts for WACCM

WACCM members in ACOM that can help:

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Other co-chairs from the Whole Atmosphere Working Group of CESM:

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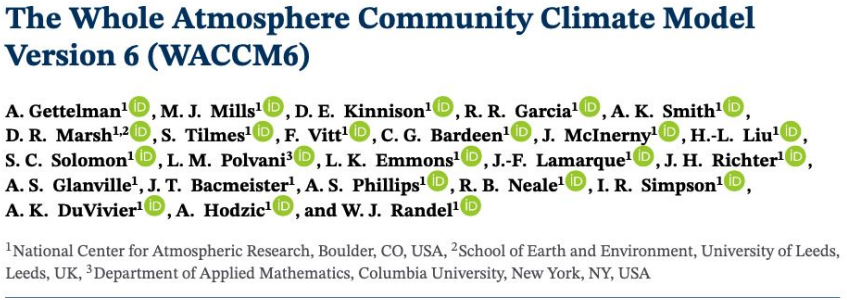

The Whole Atmosphere Community Climate Model Version 6 (WACCM6)

A. Gettelman[1], M. J. Mills[1], D. E. Kinnison[1], R. R. Garcia[1], A. K. Smith[1], D. R. Marsh[1,2], S. Tilmes[1], F. Vitt[1], C. G. Bardeen[1], J. McInerny[1], H.-L. Liu[1], S. C. Solomon[1], L. M. Polvani[3], L. K. Emmons[1], J.-F. Lamarque[1], J. H. Richter[1], A. S. Glanville[1], J. T. Bacmeister[1], A. S. Phillips[1], R. B. Neale[1], I. R. Simpson[1], A. K. DuVivier[1], A. Hodzic[1], and W. J. Randel[1]

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